Cosmic Rays from Gamma Ray Bursts

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1. Origin of Cosmic Rays: A Complete Model
2. Neutrinos from GRBs: Test of GRB/Cosmic Ray model
3. Evidence for Cosmic Ray Acceleration in GRBs: GRB 941017
4. Cosmic Rays from GRBs in the Galaxy

Vietri (1995), Waxman (1995), Milgrom and Usov (1995), Dar and Plaga (1999), Dar et al., Dermer and Humi (2001), Dermer (2002),…

Cosmic Ray Energy Spectrum at High (> 10^{14} eV/nuc) Energies

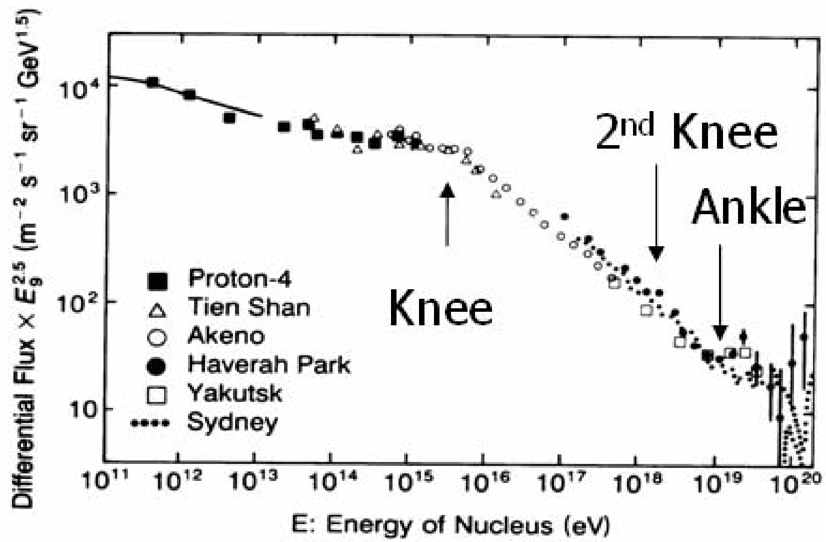
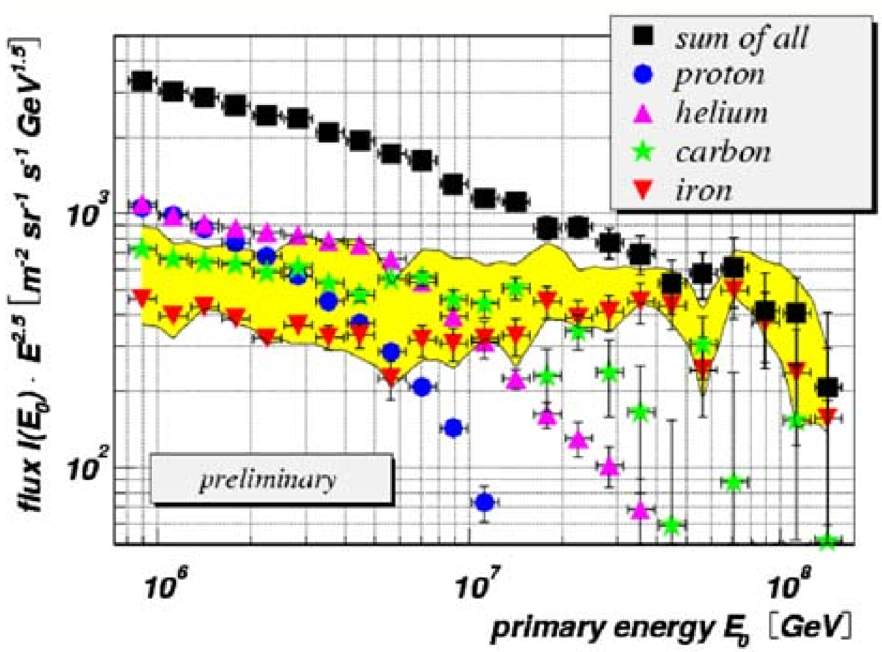


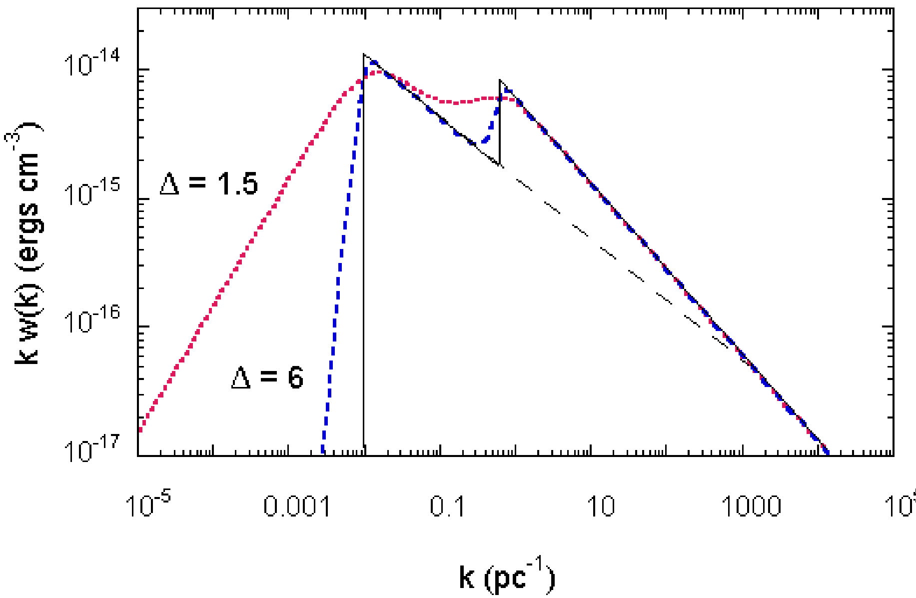
Figure 2. Cosmic ray energy spectrum multiplied by $E^{2.5}$ t
better show the spectral variations. (*Adapted from Hillas, 1984*

- Steepening above "knee" at ≈ **3×10^{15} eV**
- Second knee at ≈ **$10^{17.4}$ eV**
- Flattening above "ankle" at ≈ **$5\text{x}10^{18}$ eV**
- Ultra-high energy cosmic rays (UHECRs) > **$5\text{x}10^{18}$ eV**

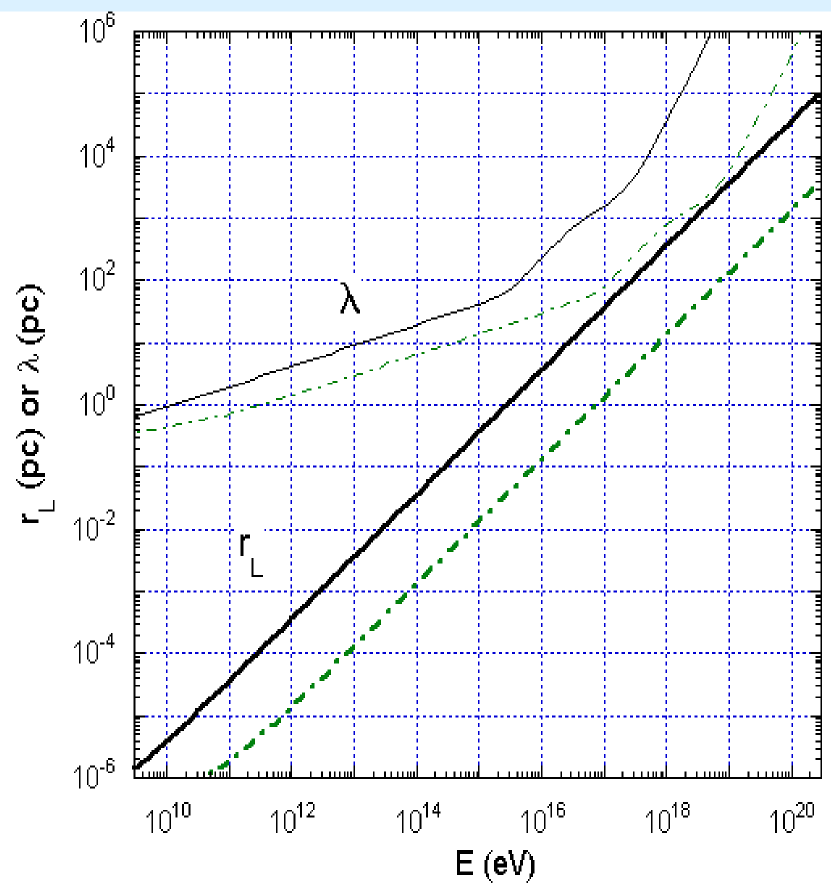
- Preliminary (2001) KASCADE results on the Knee of the Cosmic Ray Spectrum
- Break in total energy $E \propto Z$ (rigidity; gyroradii r_L=E/QB)



Diffusion of Cosmic Rays due to Pitch Angle Scattering



Cosmic rays diffuse through stochastic gyro-resonant pitch-angle scattering with MHD wave turbulence.



Larmor Radius: $$r_L = \frac{mc^2\gamma}{qB} \cong \frac{(\gamma/10^6)}{ZB_{\mu G}}\,pc$$

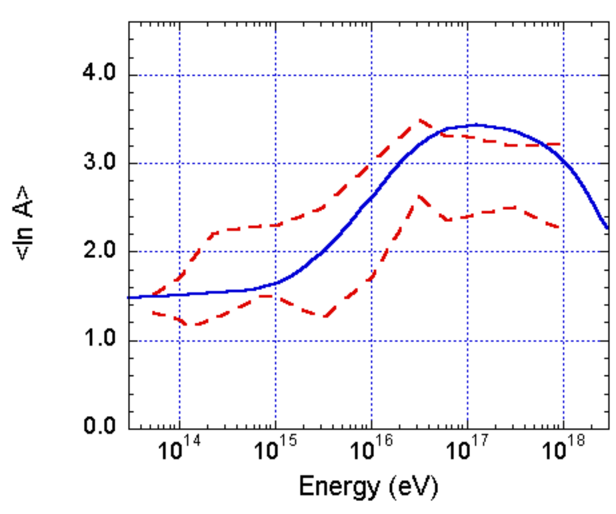
Mean free path λ for deflection by π/2:

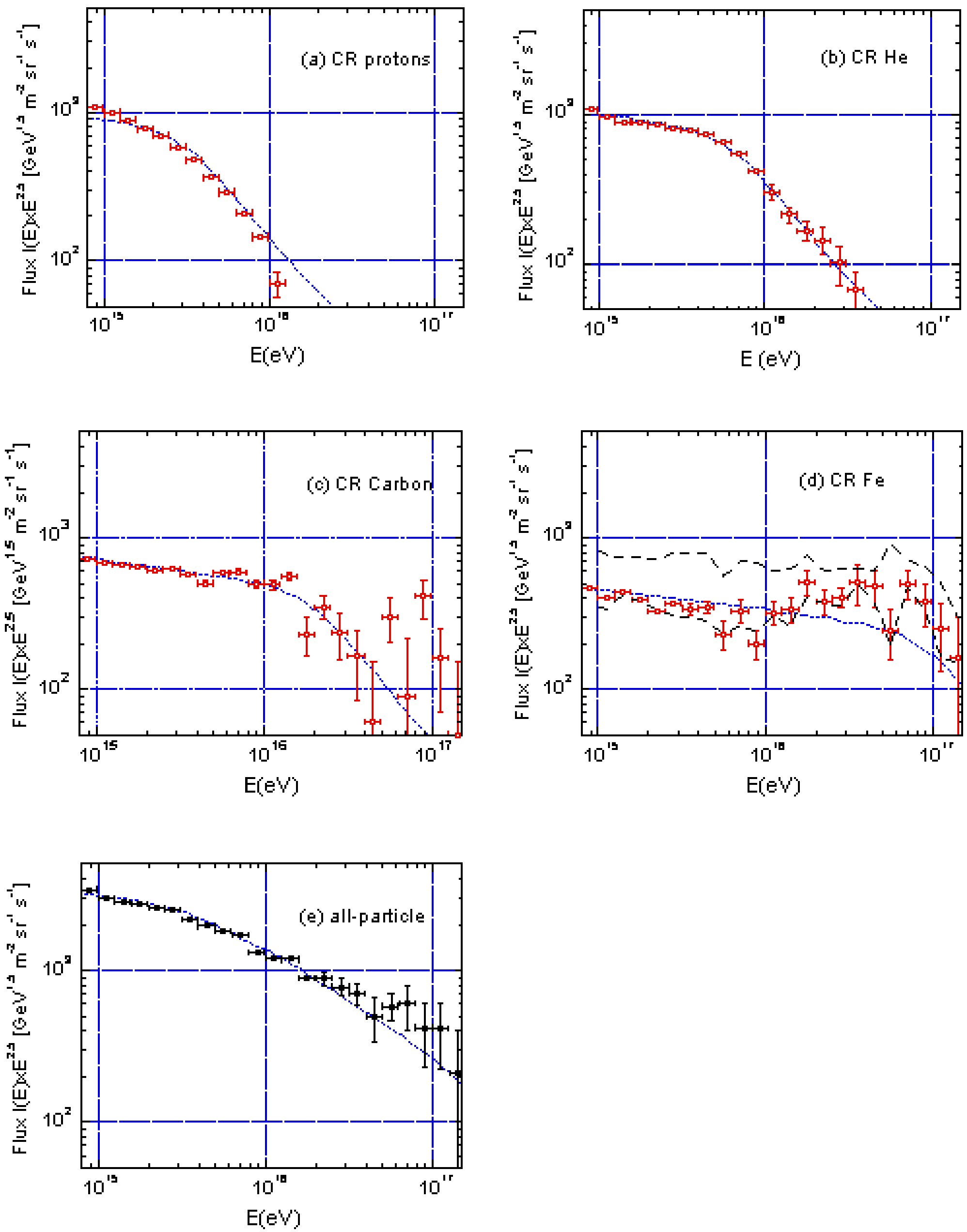
$$\lambda = \frac{U_B}{\bar{k}w(\bar{k})} r_L \, ; \bar{k} = 1/r_L$$

Fits to KASCADE Data through the Knee of the Cosmic Ray Spectrum

GRB occurred ~2x10^5 years ago at a distance of ~500 pc

- Likelihood of event
- Anisotropy





Energy-loss Mean Free Path of UHECR Protons on CMBR Photons

Energy Losses

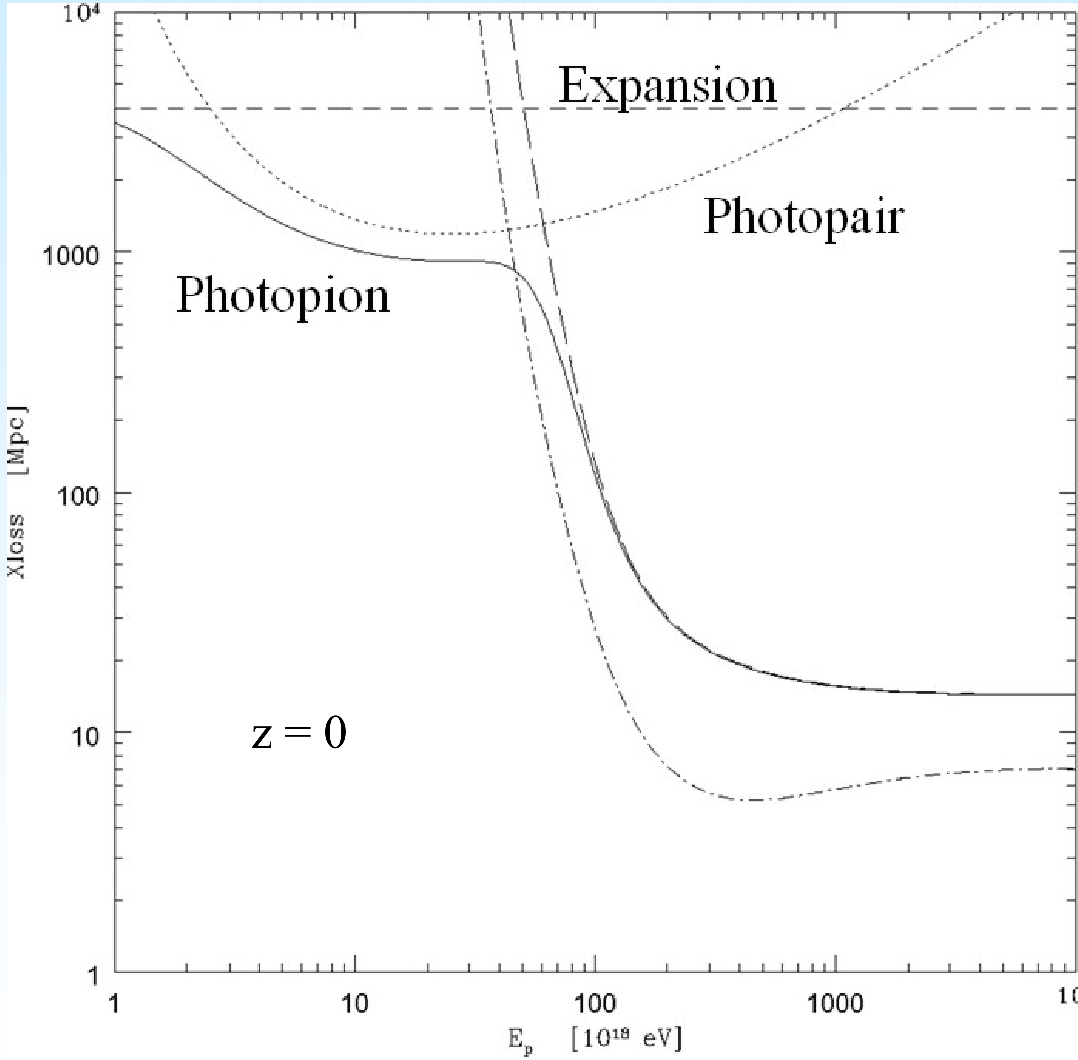
- Photopair

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

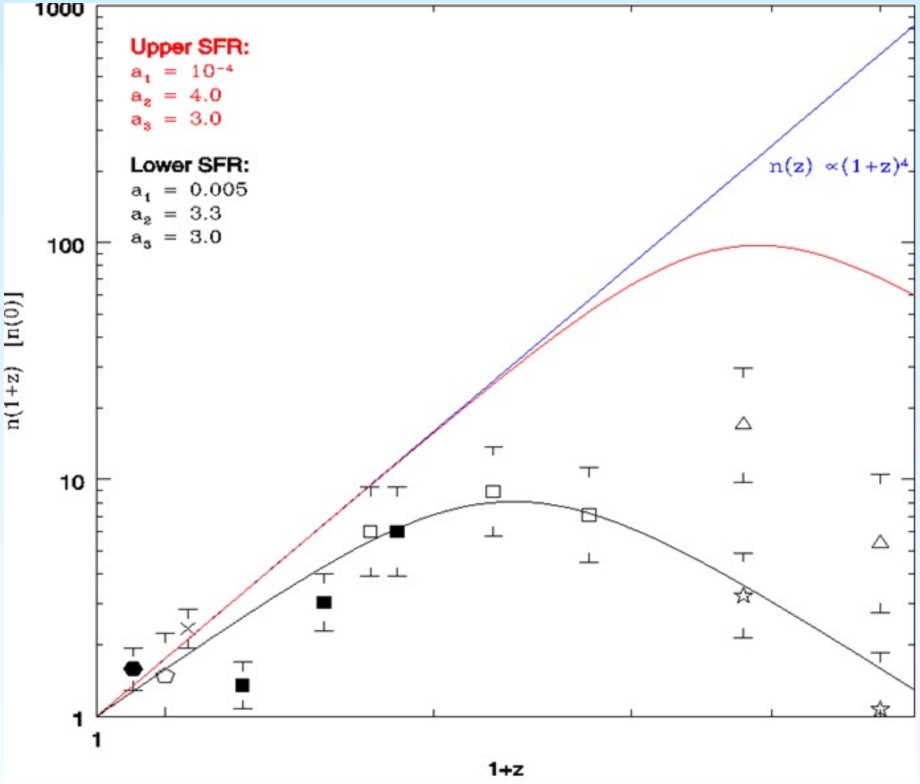
- Photopion

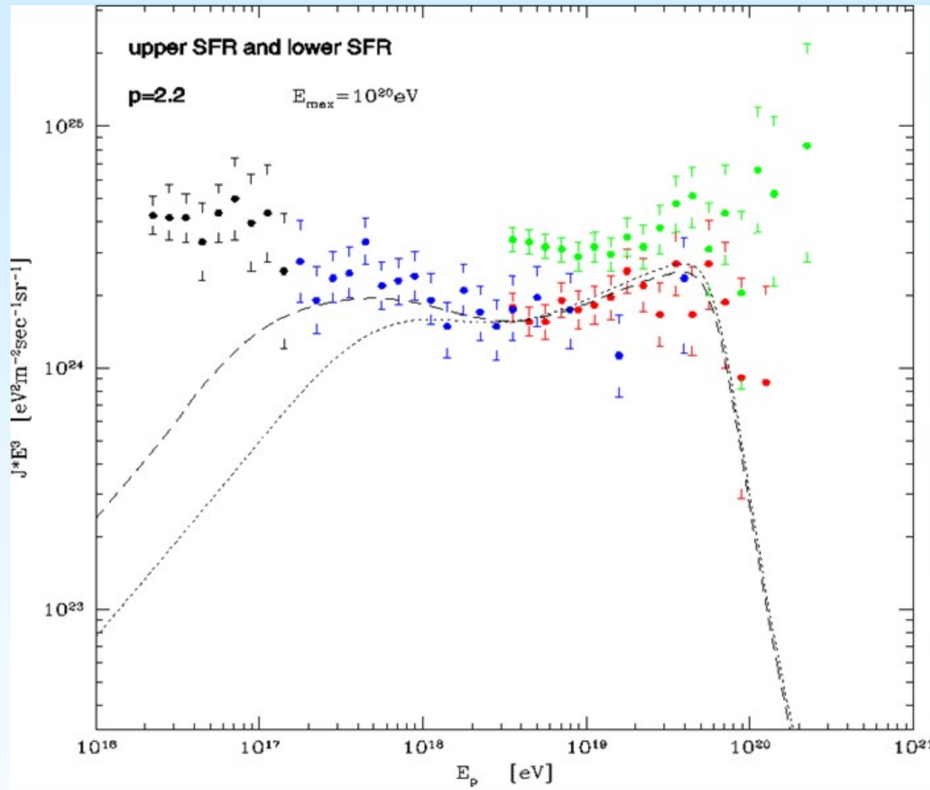
$$p + \gamma \rightarrow \pi^{\pm,0}$$

- Expansion



Effects of Star Formation Rate on UHECR Spectrum





Assume luminosity density of GRBs follows SFR history of universe

Best Fit to High Energy Cosmic Ray Data

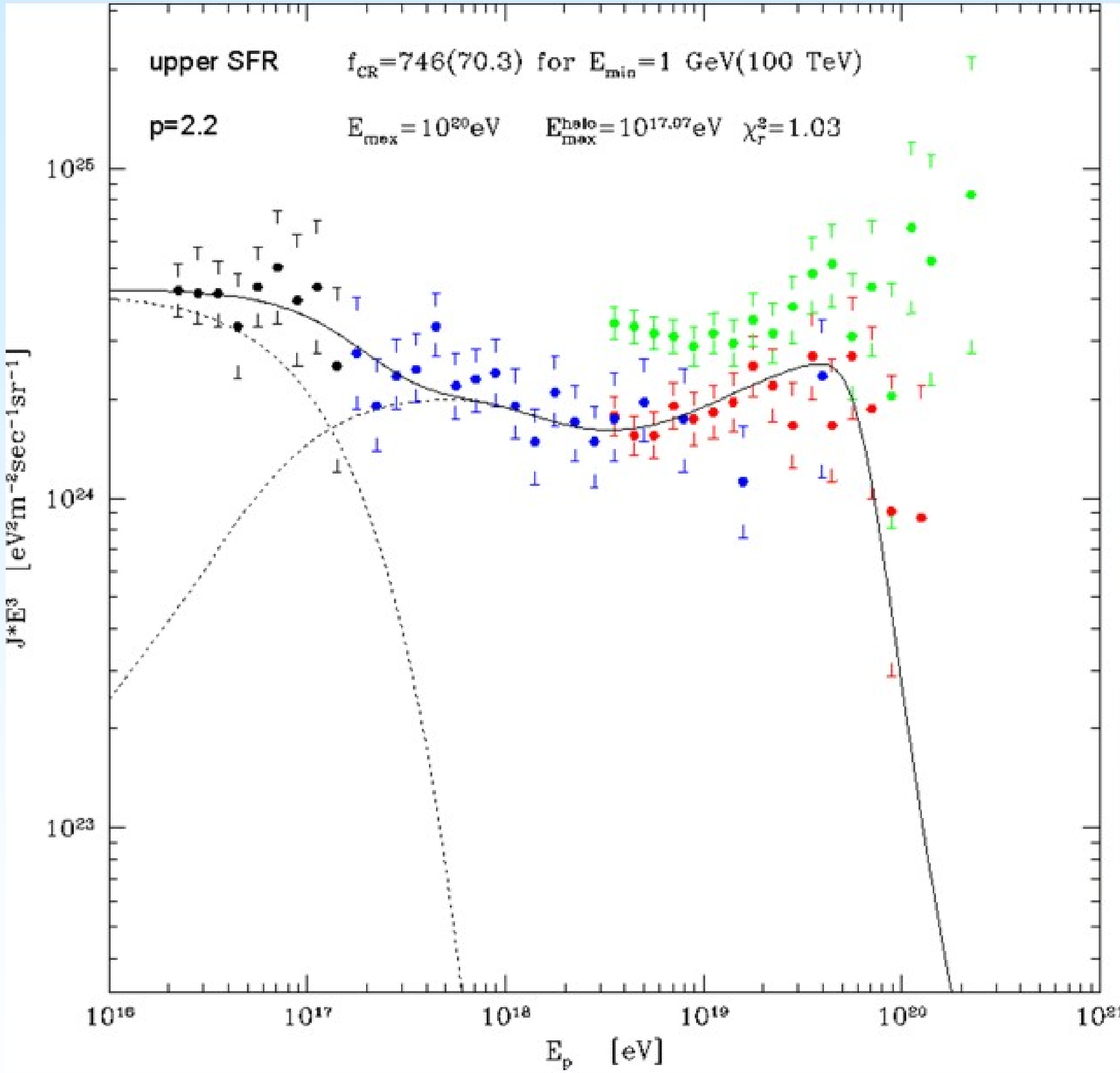
Inject -2.2 spectrum (relativistic shock acceleration index)

Better fit with upper SFR

“Second knee” at transition between galactic and extragalactic components

Fits to KASCADE and HiRes data imply local luminosity density of GRBs

Requires large baryon load: $f_b \sim 50\text{-}200$

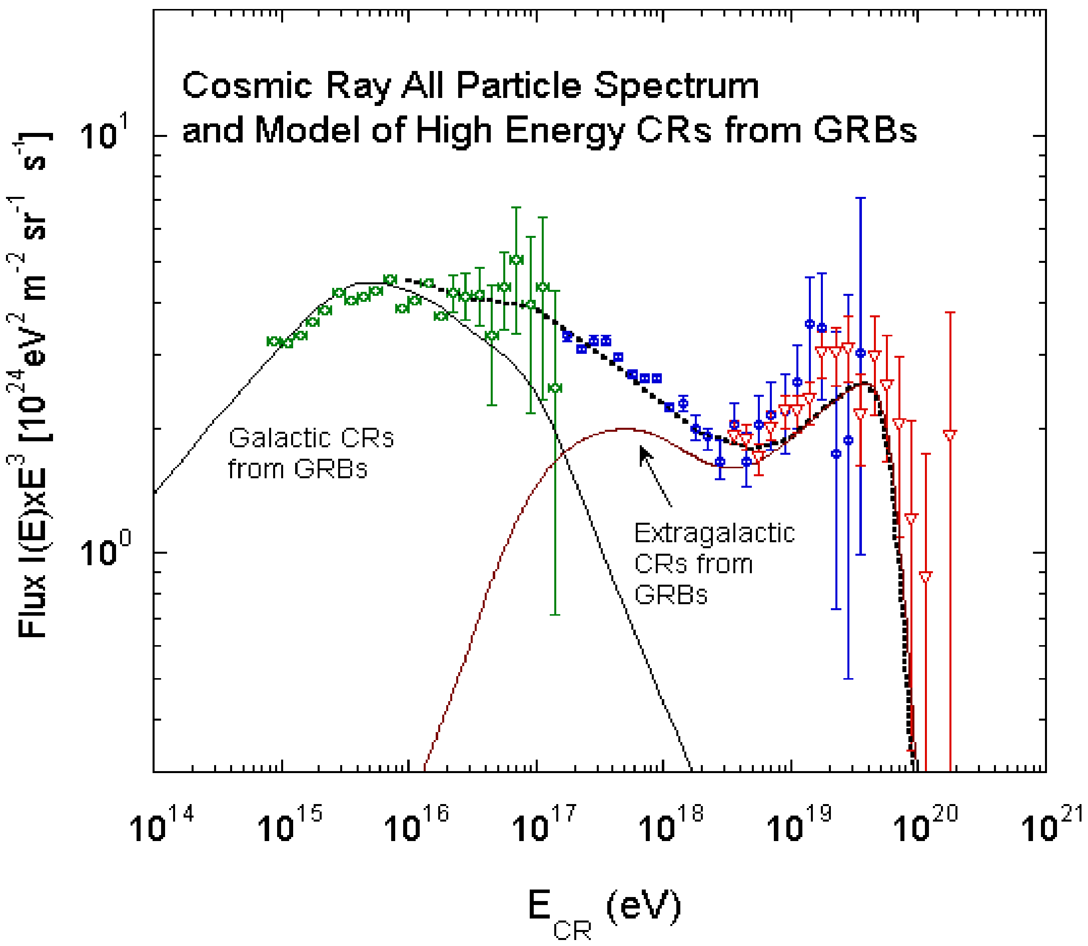


Complete Solution to the Problem of CR Origin

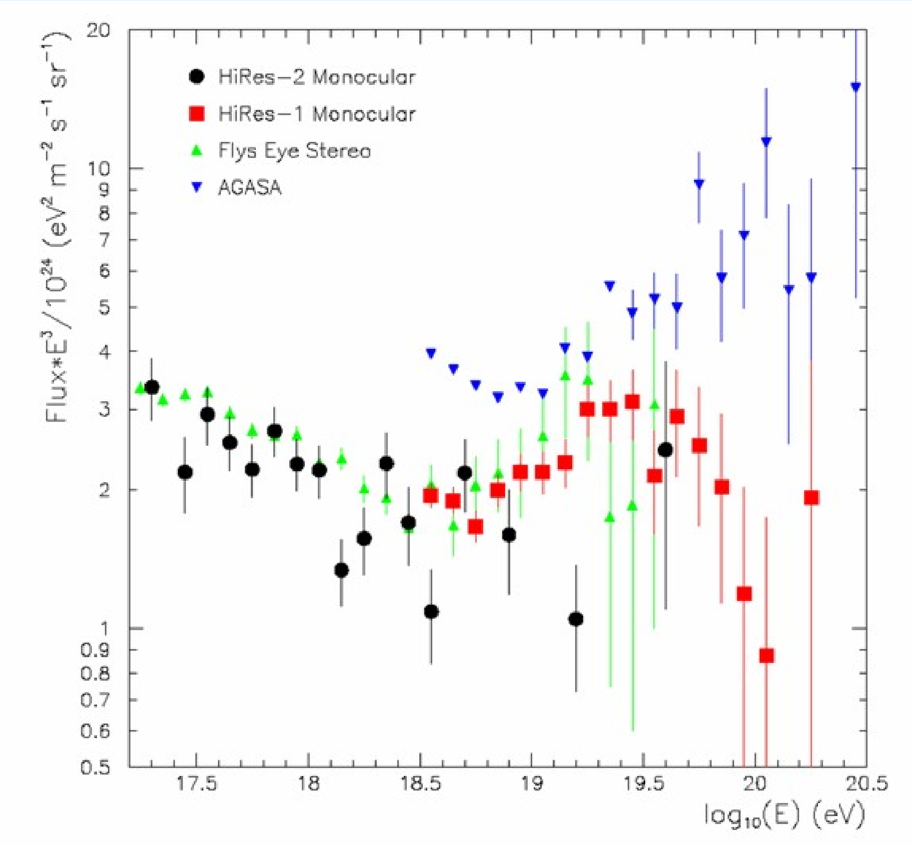
(Wick et al. 2004)

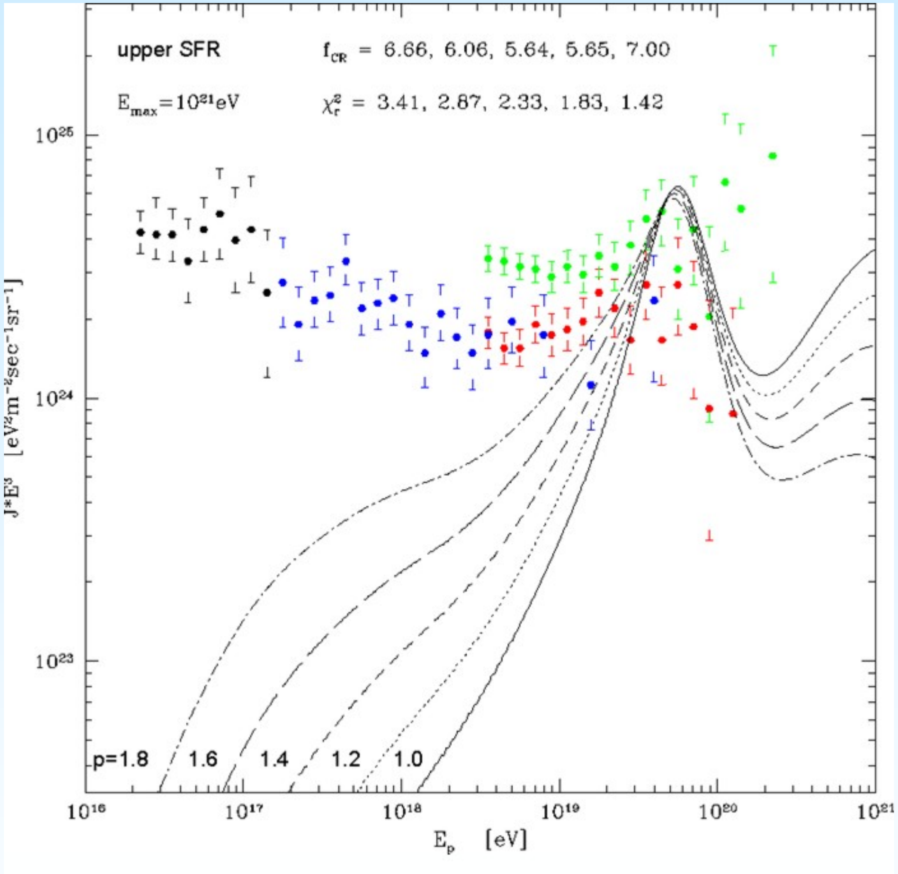
- Cosmic Rays below ≈ 10^{14} eV from SNe that collapse to neutron stars

- Cosmic Rays above ≈ 10^{14} eV from SNe that collapse to black holes
  - CRs between knee and second knee from GRBs in Galaxy
  - CRs at higher energy from extragalactic/ cosmological origin



Fits to AGASA Data





- Fit highest energy points with hard injection spectrum
- Requires other sources for lower energy cosmic rays

- GRB model implies AGASA results not valid
- If correct, points to new physics
- Will be resolved with Auger

2. Neutrinos from GRBs

Standard Fireball/Blast Wave Model

Leptonic emission processes:

1. Nonthermal synchrotron
2. Compton scattering

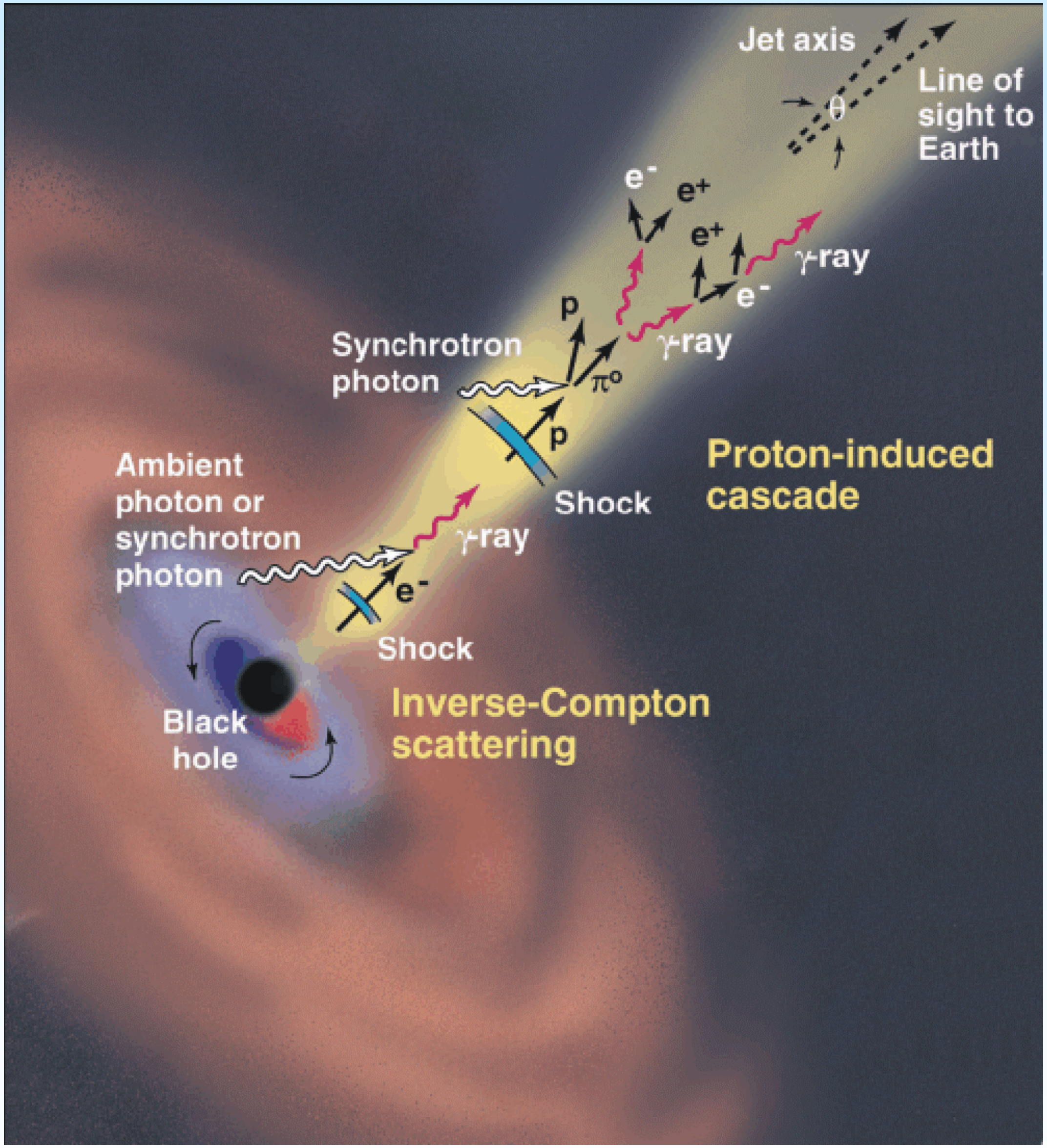
$$\varepsilon_e \sim 0.1$$

Hadronic emission processes:

1. Photopion production
2. Cascade radiation

$$p\gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm}\ (+n, p, \nu)$$

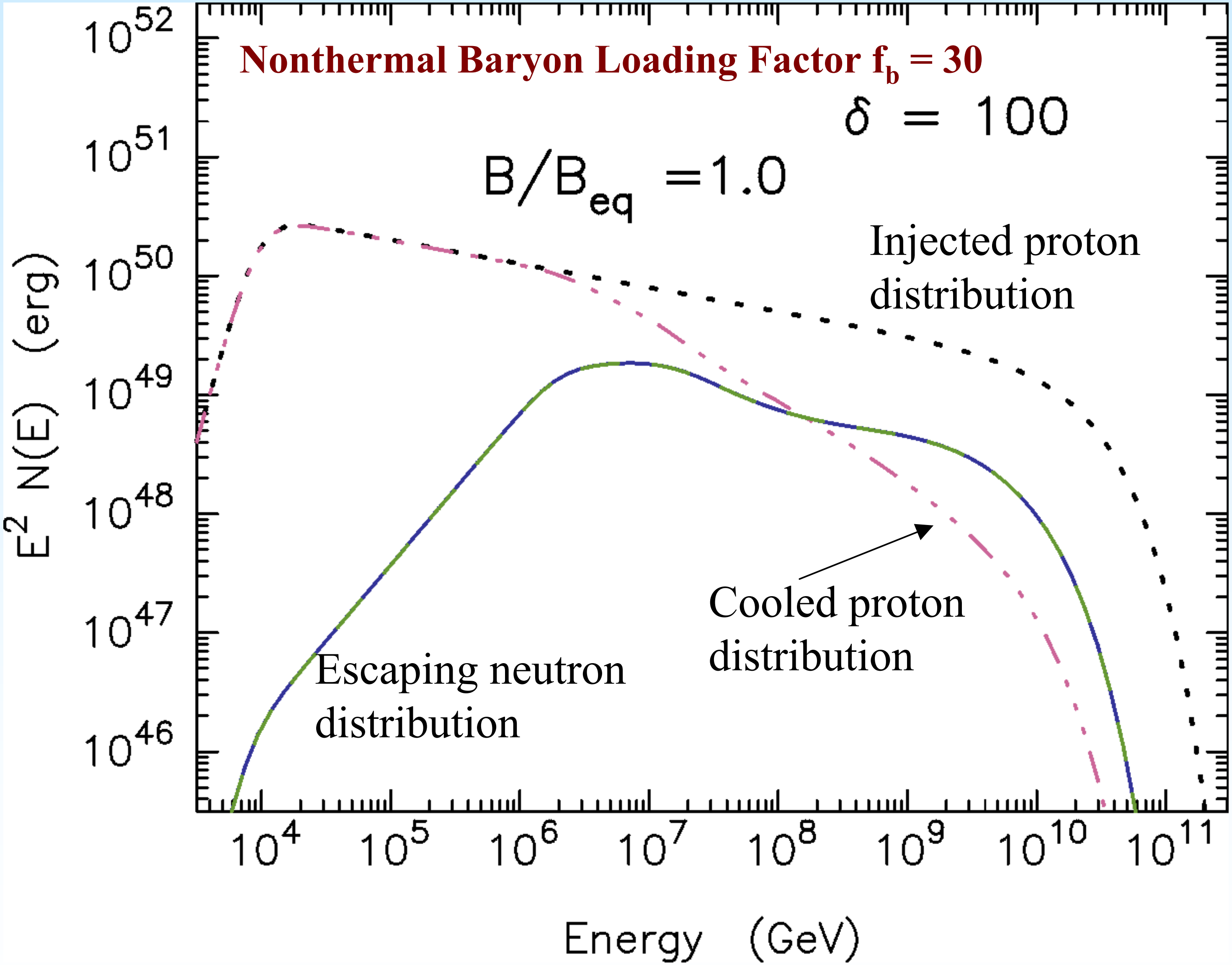
$$\rightarrow \pi^{0} \rightarrow 2\gamma \rightarrow e^{\pm}$$



Proton Injection and Cooling Spectra

GRB synchrotron fluence

$\Phi_{tot} = 3\times10^{-5}$ $ergs\ cm^{-2}$, 50 *one* sec *pulses*



Photomeson Cascade Radiation Fluxes

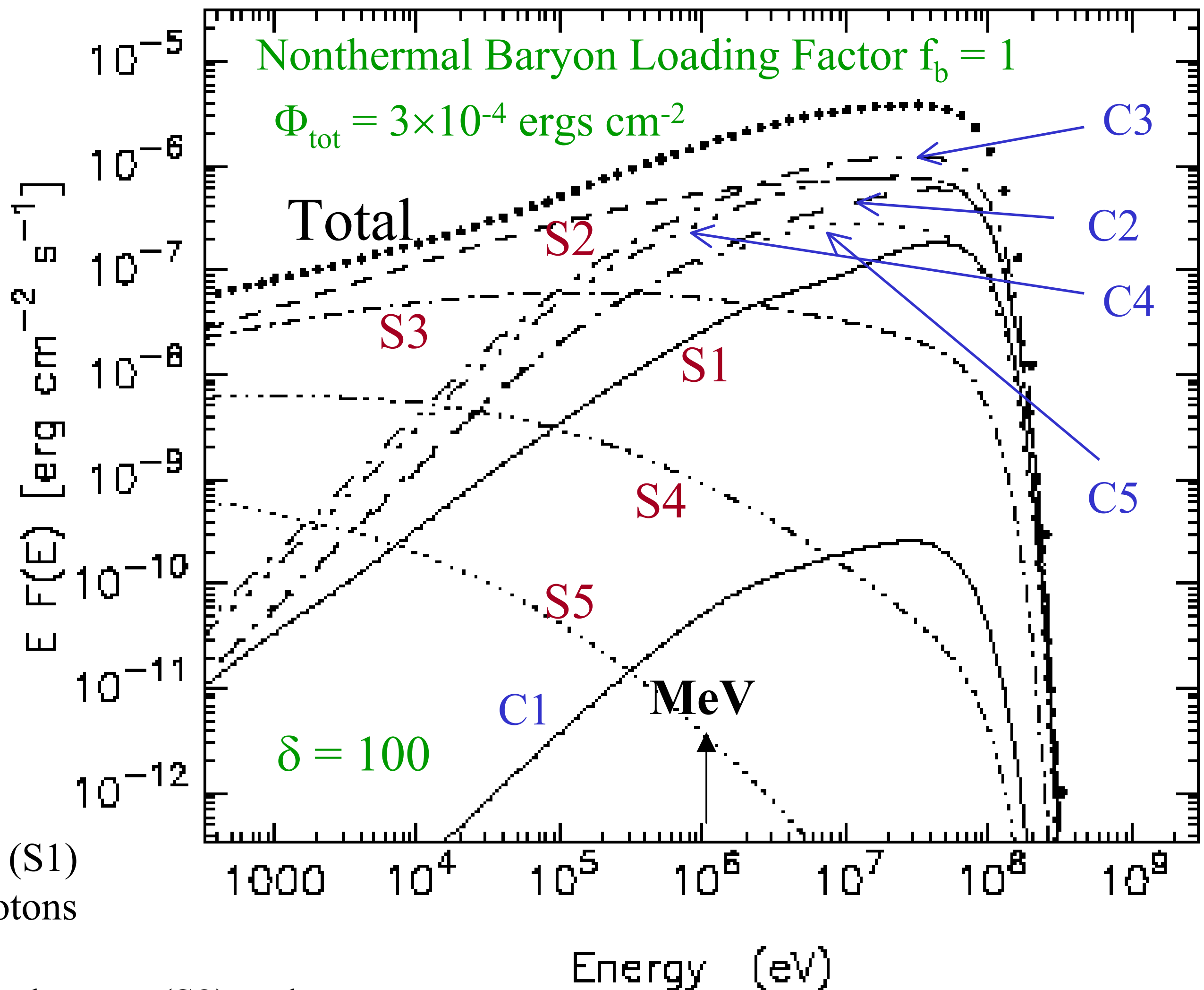
Photon index between −1.5 and −2

Fits data for GRB 941017 spectrum during prompt phase

Photomeson Cascade:

$$p\gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm}$$

$e^{\pm}$ emits synchrotron (S1) and Compton (C1) photons



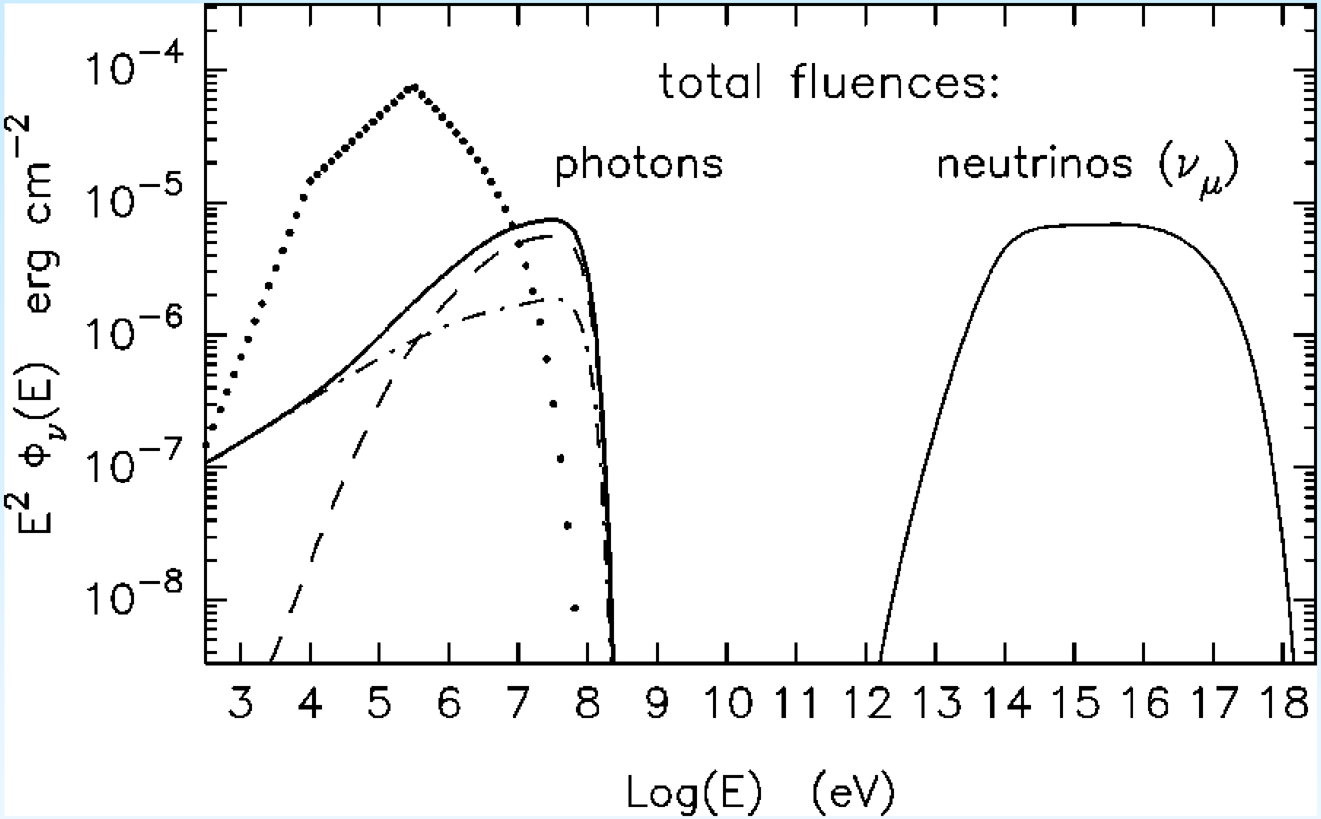
$$\gamma\gamma' \rightarrow e^{\pm}$$ emits synchrotron (S2) and Compton (C2) photons, etc.

Photon and Neutrino Fluence during Prompt Phase

Nonthermal Baryon Loading Factor $f_b = 1$

$\Phi_{tot} = 3\times10^{-4}$ ergs cm^{-2}

$\delta = 100$



Hard γ-ray emission component from hadronic cascade radiation inside GRB blast wave with associated outflowing high-energy neutral beam of neutrons, γ-rays, and neutrinos

$$p\gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm}\ (+n, p, \nu)$$
$$\rightarrow \pi^{0} \rightarrow 2\gamma \rightarrow e^{\pm}$$

Fluence of Photomeson Muon Neutrinos

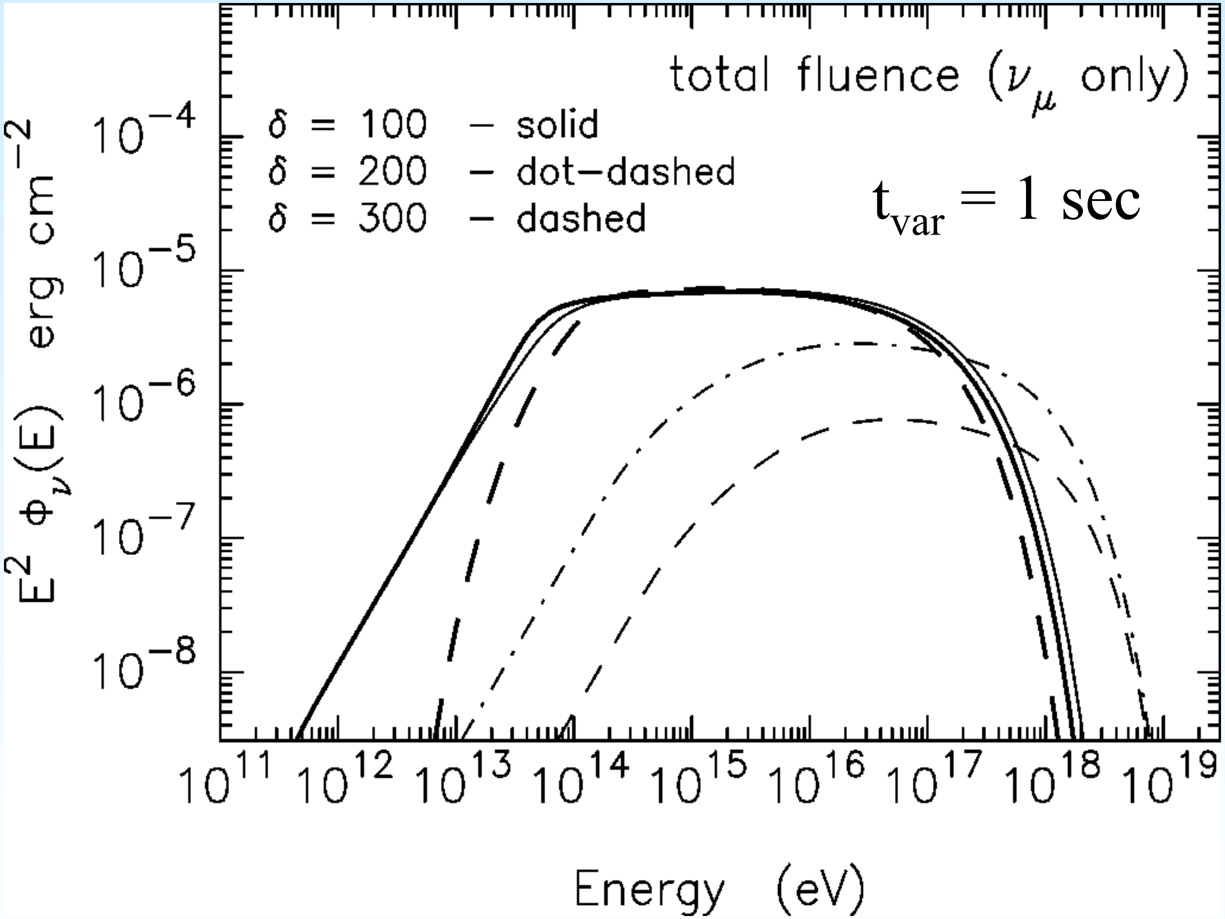
For a fluence of $3x10^{-5}$ ergs/cm^2 (~30 - 40/yr)

N_ν detected by IceCube:

$N_\nu \approx$ 0.0032, 0.00015, 0.00001 for δ = 100, 200, and 300, respectively in collapsar model

$N_\nu \approx$ 0.009 for δ = 100 and 300 in supranova model

Nonthermal Baryon Loading Factor f_b = 1



Dermer and Atoyan, PRL, 2003

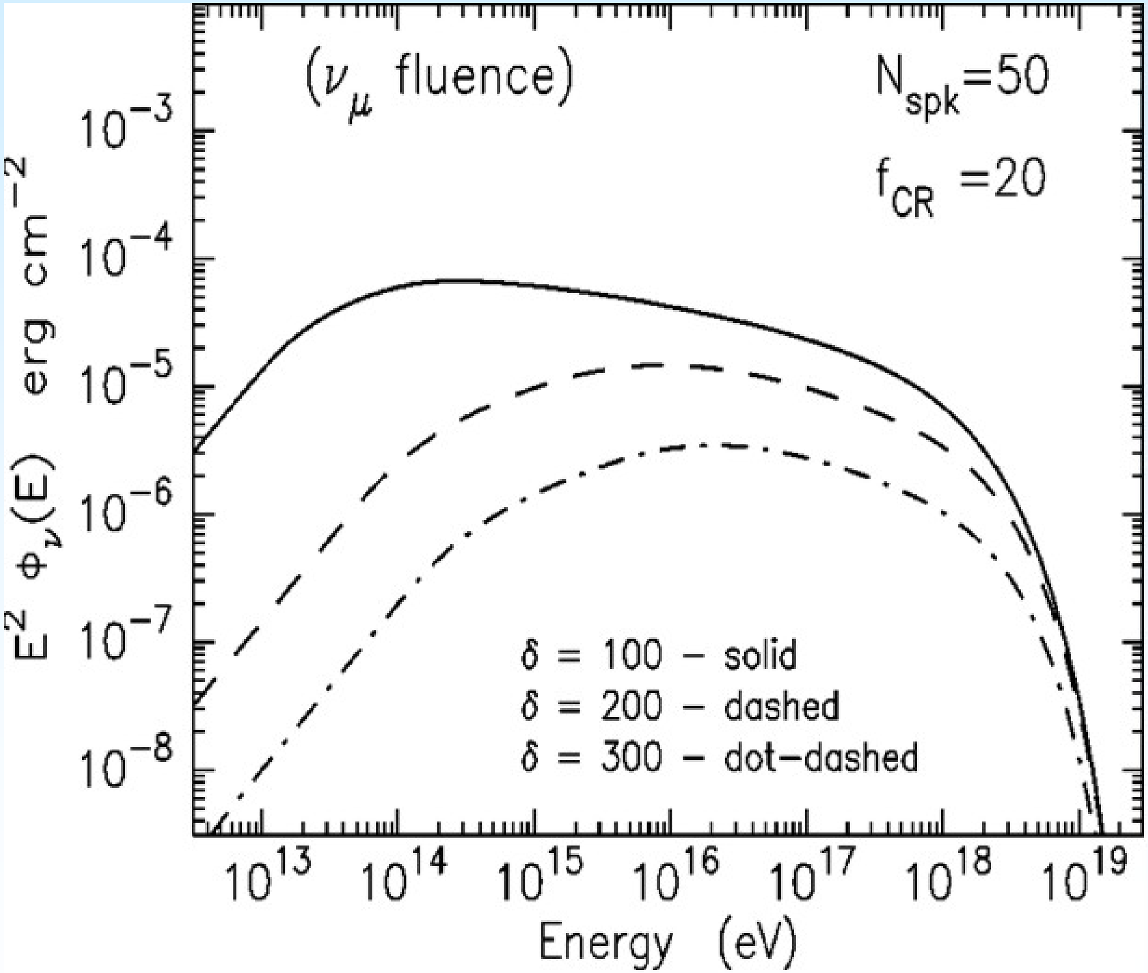
Neutrino Detection from GRBs only with Large Baryon-Loading

For a fluence of $3x10^{-4}$ ergs/cm^2, (~2/yr)

N_ν predicted by IceCube:

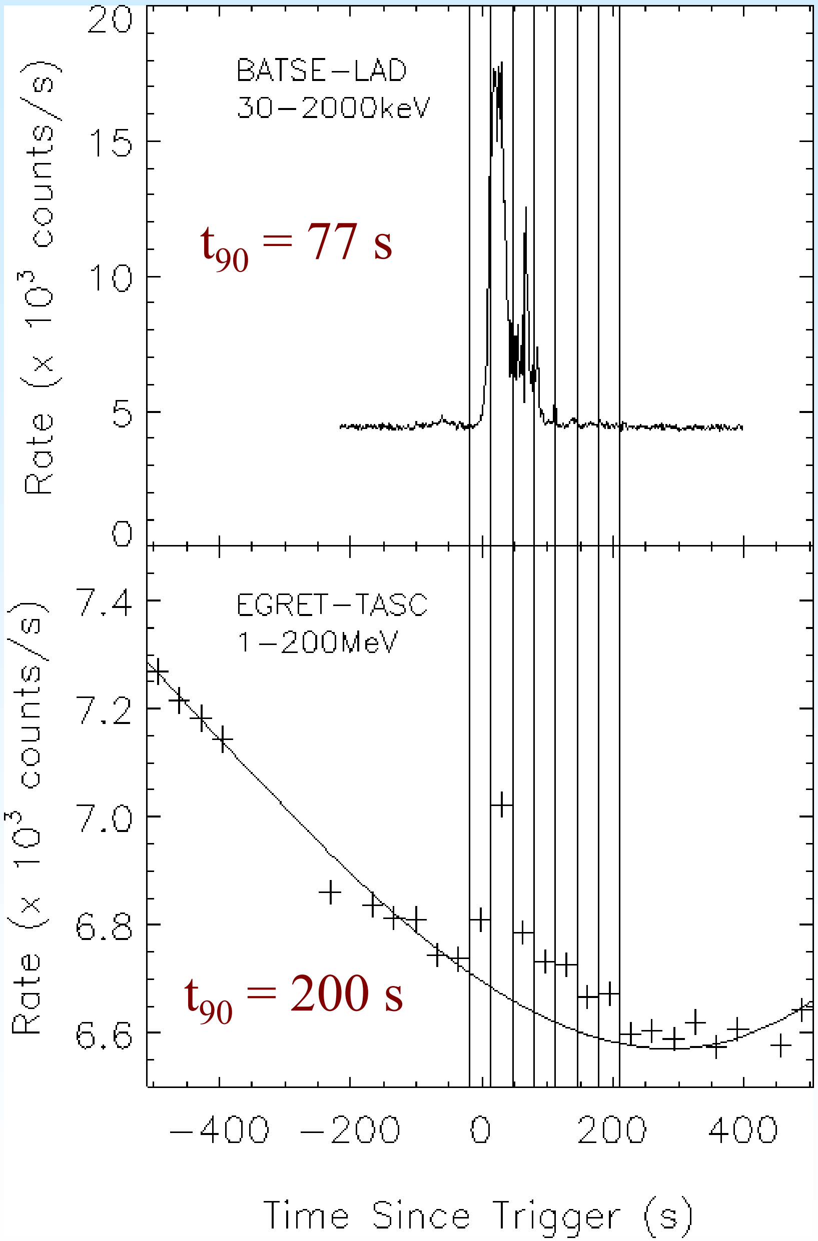
$N_\nu \approx$ 1.3, 0.1, 0.016 for δ = 100, 200, and 300, respectively in collapsar model for f_{CR} = 20

Nonthermal Baryon Loading Factor f_b = 20

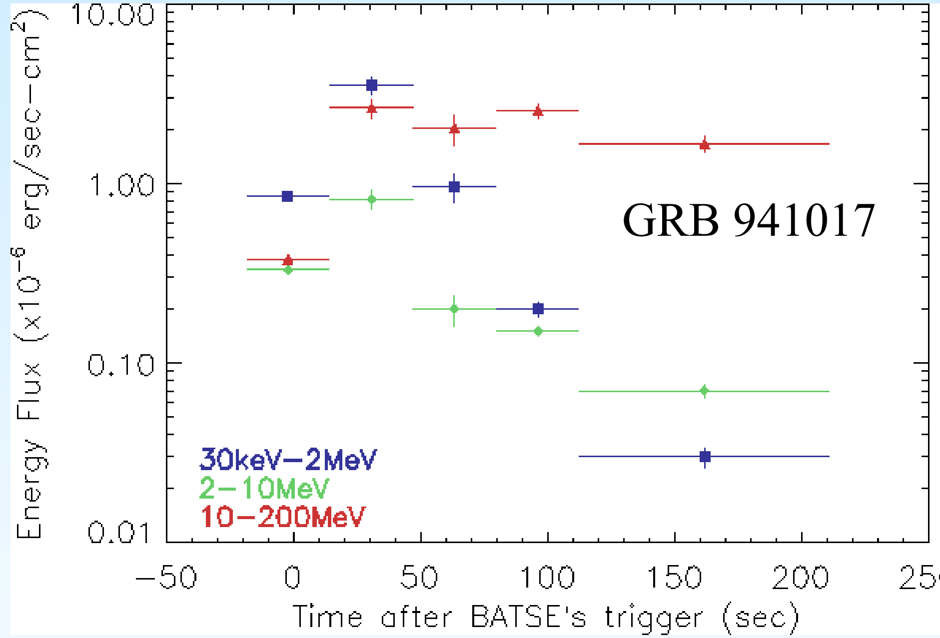


3. Evidence for Cosmic Rays in GRBs: The Case of GRB 941017

GRB 941017 Light Curves



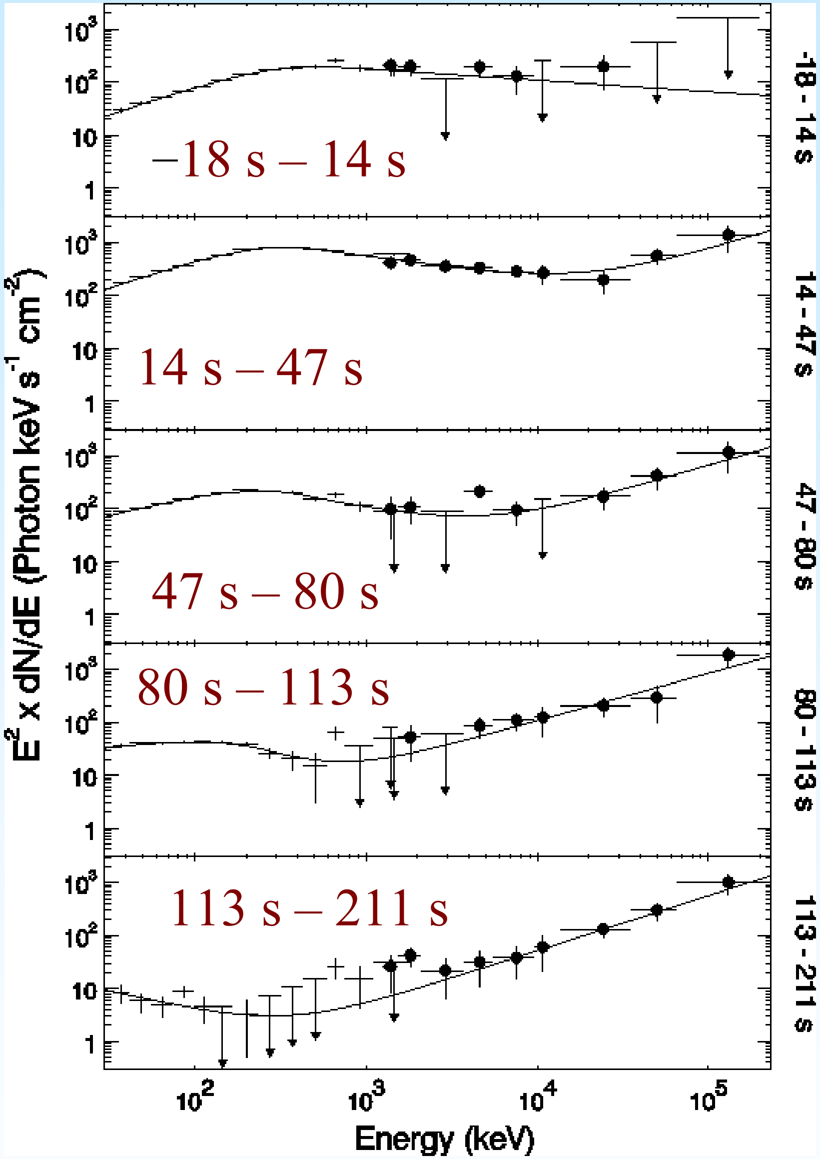
González et al., Nature (2003)

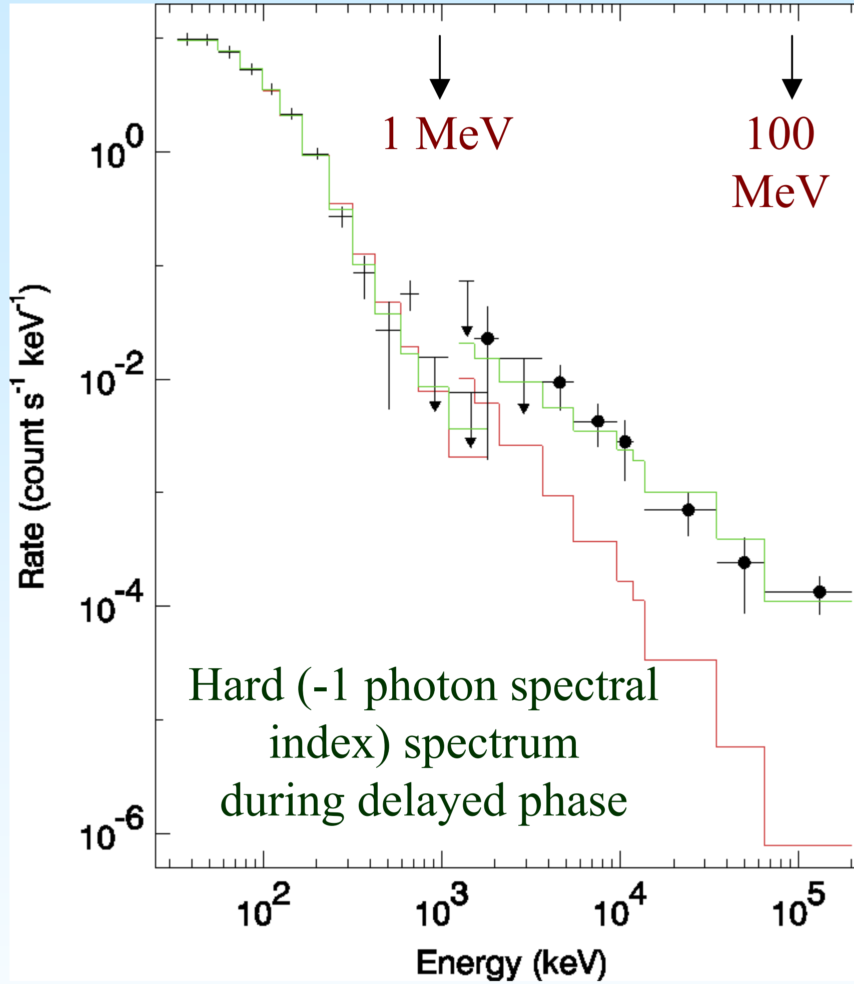


Analyzed 26 BATSE/TASC GRBs

GRB 941017: 11th highest fluence GRB in BATSE catalog

Anomalous γ-ray component now seen in 2 other GRBs





Fluence, including hard γ-ray component, is > 6.5 10^{-4} ergs cm^{-2}

Typical hard-to-soft evolution of GRBs

Hard component observed both with BATSE and TASC

Leptonic Models for γ-ray Emission Components in GRB 941017

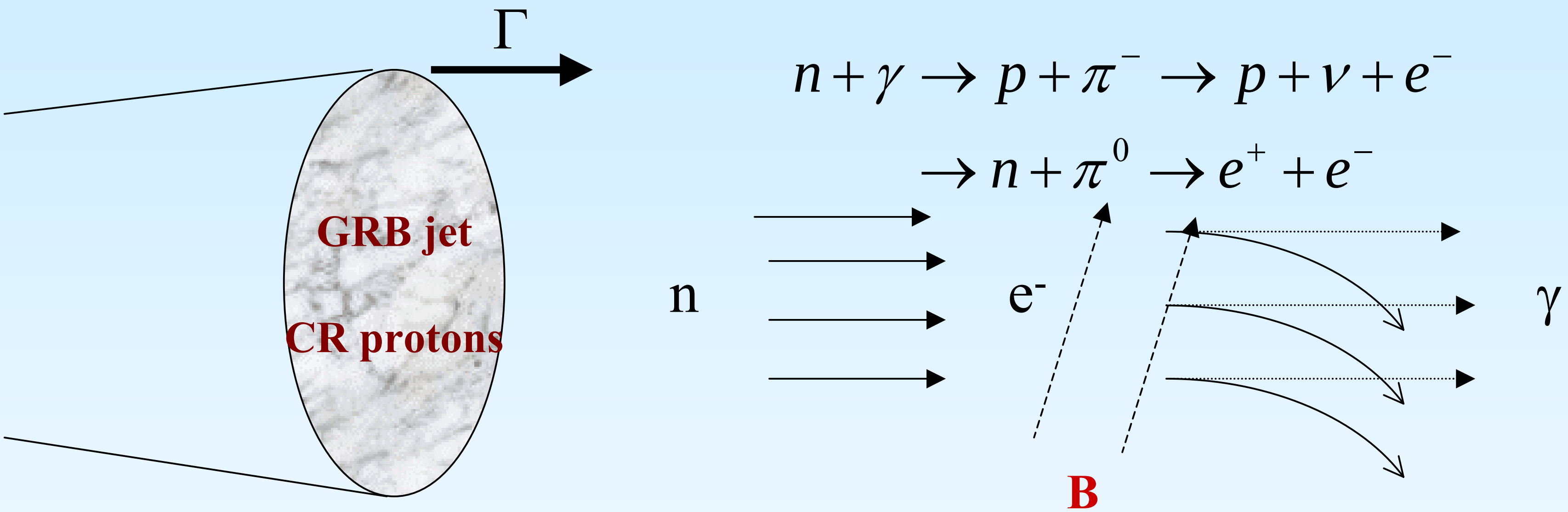
- Major difficulty is that >10 MeV γ-ray component increases while < 2 MeV synchrotron component decays

- Comptonization of reverse shock emission by forward shock electrons (but requires extreme parameters) (Granot and Guetta 2003; Pe'er and Waxman 2004)

Neutral Beam Model for Anomalous γ-rays in GRB 941017

$$n + \gamma \rightarrow p + \pi^{-} \rightarrow p + \nu + e^{-}$$

$$\rightarrow n + \pi^{0} \rightarrow e^{+} + e^{-}$$



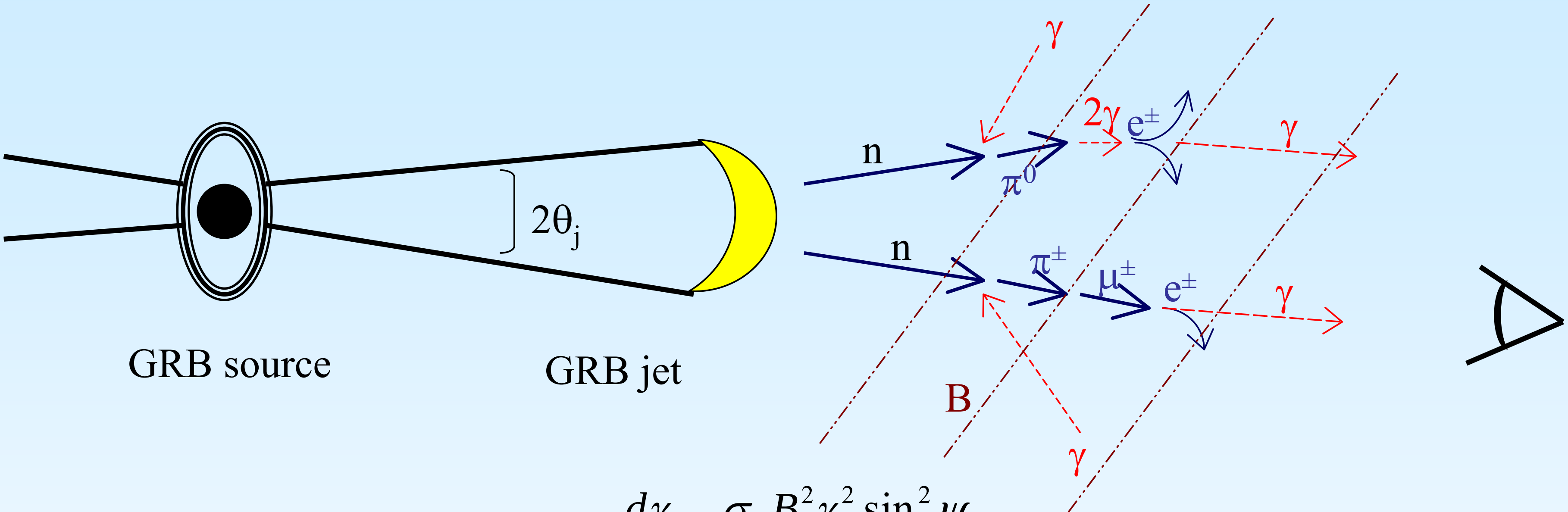
Hadronic cascade radiation in jet

Escaping neutron beam forming hyper-relativistic electrons/positrons

Highly polarized nonthermal synchrotron radiation

Neutral Beam Model (Atoyan and Dermer, ApJ, 2003) for blazar jets
Two hadronic emission components

Radiation Physics of Neutron/Hyper-relativistic Electron Beam



Synchrotron energy-loss rate: $-\frac{d\gamma}{dt} = \frac{\sigma_T B^2 \gamma^2 \sin^2\psi}{4\pi m_e c}$

Synchrotron energy-loss timescale: $t_{syn} = \gamma / |\frac{d\gamma}{dt}|$

Gyration frequency: $\omega_B = eB / m_e c\gamma\,|$

When $\omega_B t_{syn} << 1$, hyper-relativistic electrons

When $\omega_B t_{syn} << \theta_j$, electrons emit most of their energy within θ_j

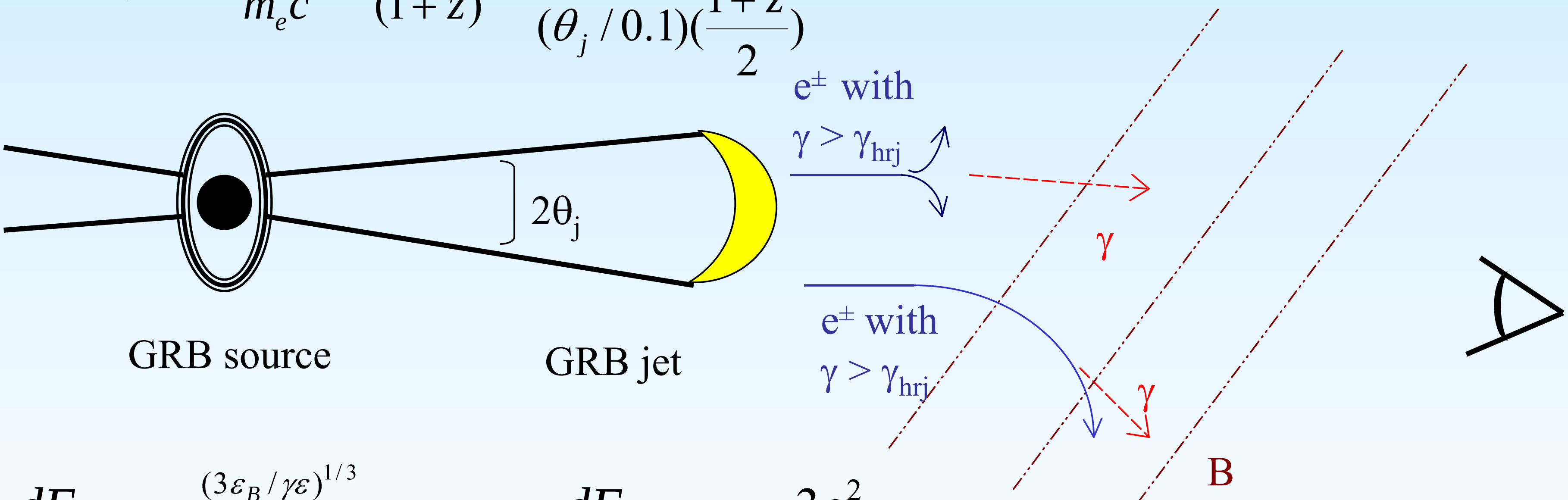
$$\boxed{\gamma_{hr} \geq \frac{1\times 10^8}{\sqrt{B(G)\sin\psi}}}$$

$$\boxed{\gamma \geq \gamma_{hrj} = \frac{3\times 10^8}{\sqrt{(\theta_j / 0.1) B(G)\sin\psi}}}$$

Hyper-relativistic Electron Synchrotron Radiation

Mean energy of synchrotron photons emitted by electrons with $\gamma = \gamma_{hrj}$:

$$h\nu_{hrj} = \frac{\hbar e B \sin\psi}{m_e c}\frac{\gamma_{hrj}^2}{(1+z)} \cong \frac{500}{(\theta_j/0.1)(\frac{1+z}{2})}$$



$$\frac{dE}{d\varepsilon} \cong 2\pi \int_0^{(3\varepsilon_B/\gamma\varepsilon)^{1/3}} d\theta \cdot \theta \cdot \left(\frac{dE}{d\varepsilon d\Omega}\right)_{syn} \cong \frac{3e^2}{\pi \lambda\!\!\!^{-}_C} \propto \varepsilon^0$$, i.e., a −1 photon spectrum

Issues:

1. $\approx$ 200 sec decay timescale
2. external radiation field **($\Rightarrow$ R $\approx 6\times10^{14}$ cm, $\theta_j \approx 0.14$ for z=1)**
3. Fluence ratio $\Rightarrow$ hadronically dominated, and large ν_μ flux

4. Cosmic Rays from GRBs in the Galaxy

Numerical simulation model of cosmic ray propagation from jetted GRBs in the Milky Way

$$\frac{d}{dt}(\gamma m\vec{v}) = \frac{q}{c}\,\vec{v}\times\vec{B}$$

Larmor radius of a particle spiraling in a magnetic field

$$r_L = \frac{mc^2\gamma}{qB} \approx \frac{\gamma/10^9}{B(\mu G)}kpc$$

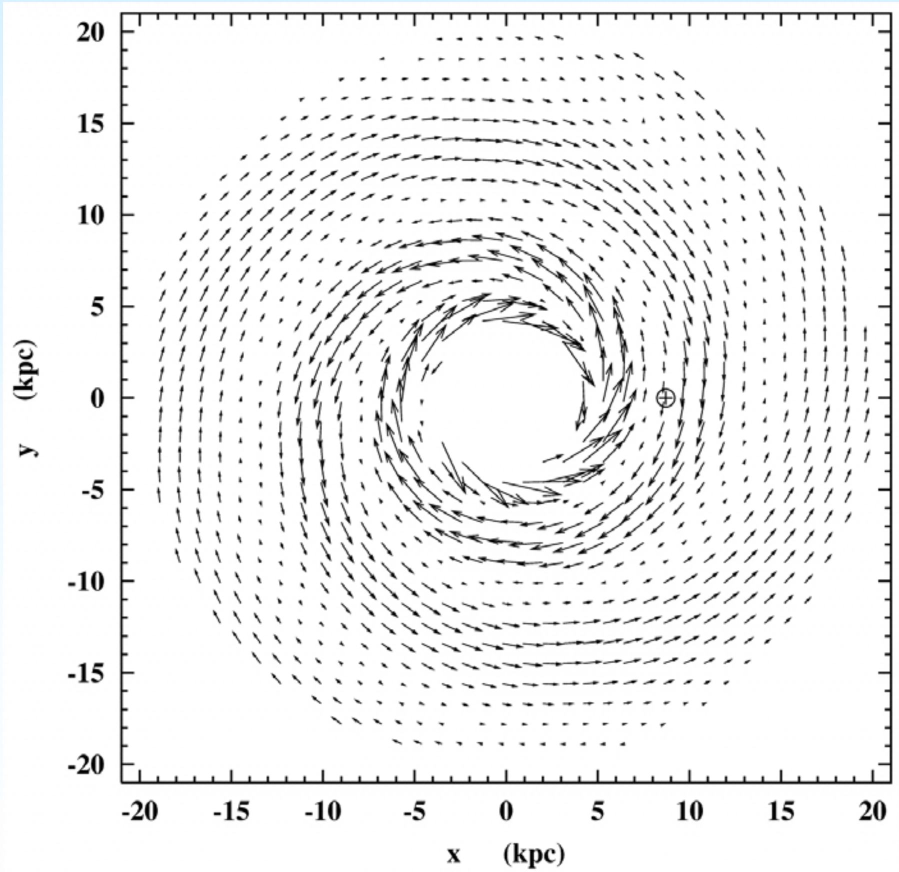
Magnetic Field Model of the Galaxy

Cosmic rays move in response to a large-scale magnetic field that traces the spiral arm structure of the Galaxy, and to pitch-angle scattering with magnetic turbulence in the Galactic magnetic field.

Disk magnetic field:

$$B(r,\phi) = B_o\left(\frac{R_\oplus}{r}\right)\cos\left(\phi - \beta \ln \frac{r}{R_o}\right)$$

Alvarez-Muniz, et al. (2000)



The typical Galactic magnetic field near Earth is 3-4 μGauss

Combined finite difference/Monte Carlo simulation for motion of cosmic ray protons and ions, and protons formed from neutron decay.

Cosmic Ray Neutrons

Neutrons are also formed in high-energy cosmic ray sources

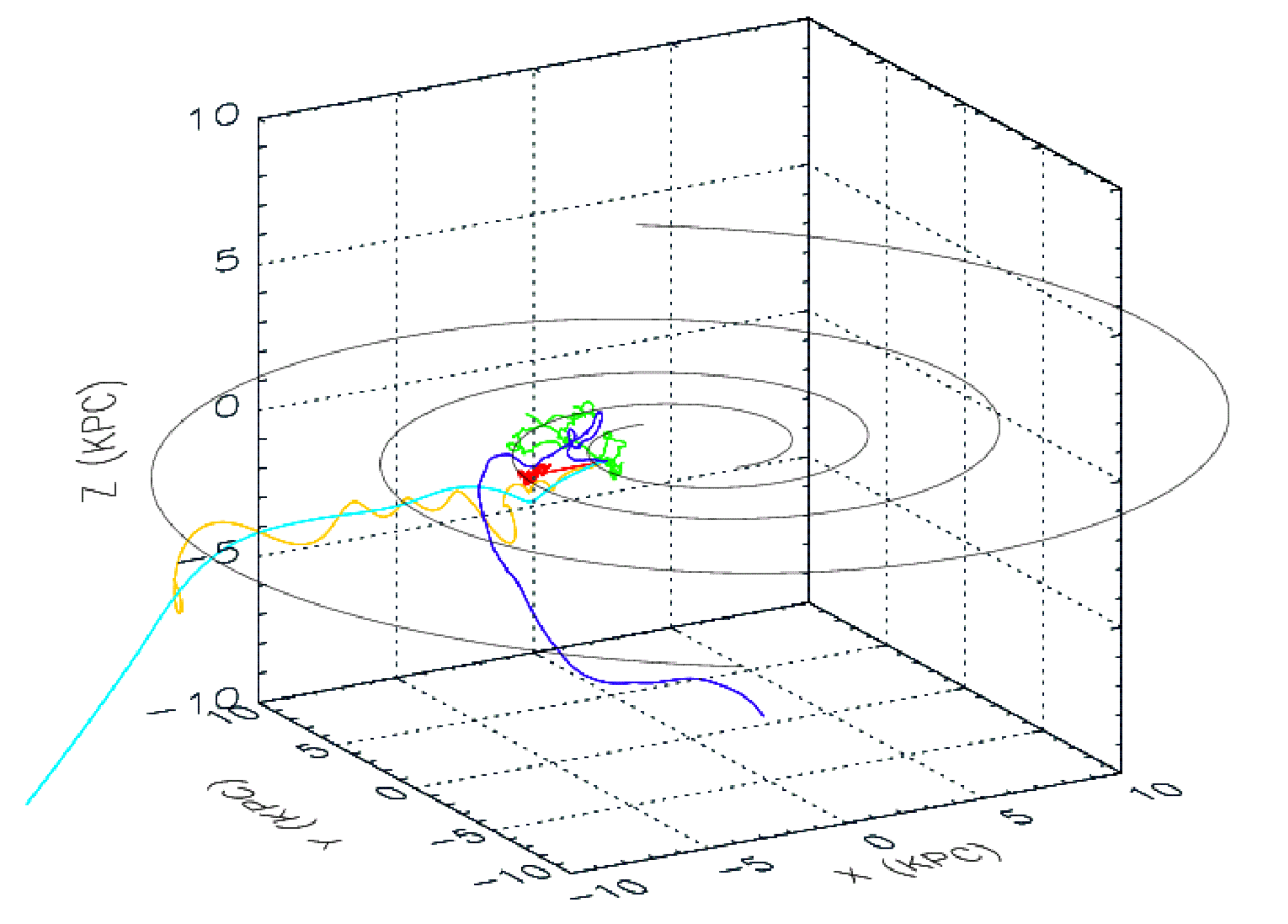
Neutrons decay on time scales of 920γ seconds, due to time dilation (about 1 kpc for $\gamma=10^8$), and then gyrate in magnetic field

Cosmic ray neutrons decay over a pathlength

$$r_n \cong ct_n\gamma \cong (\gamma/10^8)kpc$$

$$n \rightarrow p + e^- + \nu_e$$

Trajectories of Cosmic Rays in the Galaxy

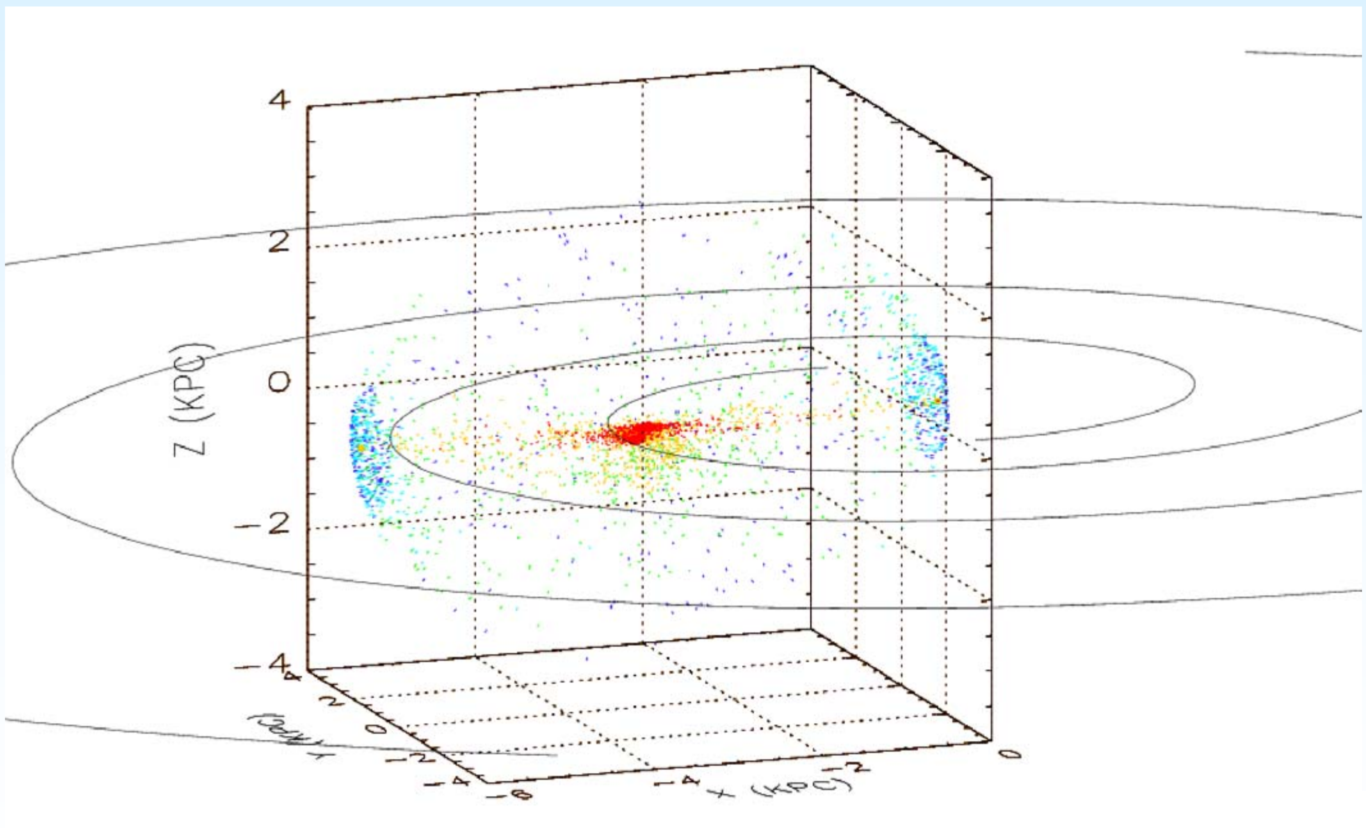


Cosmic Rays from GRBs

GRB located at 3 kpc from center of the Galaxy

GRB emission is jetted with jet opening angle of 0.1 radian

Jet is pointed radially outward along Galactic plane



Rate of GRBs in the Galaxy

- BATSE obs. imply ~ 2 GRBs/day over the full sky
- Beaming factor increases that rate by factor ~500
- Volume of the universe ~ $4\pi(4000\ \mathrm{Mpc})^3/3$
- Density of L* galaxies ~ $1/(200\text{-}500\ \mathrm{Mpc}^3)$

Rate per L* galaxy

$$\approx \frac{250\, Mpc^3 / L^*}{\frac{4\pi}{3}(4000\, Mpc)^3} \frac{1}{day} \frac{365}{yr} \times 500 f_{500} \times SFR \times K_{FT}$$

$$\approx (\frac{SFR}{1/6}) \times (\frac{K_{FT}}{3}) \frac{f_{500}}{3.5\times10^{-4}\, yr} \approx f_{500}/(12000 yrs)$$

Time-averaged power per L* galaxy (no beaming factor)

$$\approx (\frac{SFR}{1/6}) \times (\frac{K_{FT}}{3}) \times \frac{1.5\times10^{51}\ ergs}{10000\ yrs \times 3\times10^7}$$

$$\approx 5\times10^{39}(\frac{SFR}{1/6})(\frac{K_{FT}}{3})\ ergs\ s^{-1};\ \eta_\gamma = 1/3$$

K_{FT} correction factor for clean and dirty fireballs

Rate of Irradiation Events by GRBs

Fluence referred to daily Solar energy fluence

$$\varphi = S\varphi_{\circ} = 1.2\times 10^{11} S \; ergs \; cm^{-2}$$

$$S > 10^{-3}$$

for significant effects on biology. Using constant energy reservoir result implies

$$\dot{N}(>S) \approx \frac{0.03}{R_{15}^{2}}\frac{\mathrm{E}_{51}}{St_{4}}\, Gyr^{-1} \;,$$

where $10^4 t_4$ yr is the mean time between galactic GRBs, and the GRB distance is

$$R_s \approx \frac{120}{(\theta_j/0.1)}\sqrt{\frac{\mathrm{E}_{51}}{S}} \; pc$$

Effects of Cosmic Rays from Galactic GRBs

Extinction episodes (Dar, Laor & Shaviv 1998)

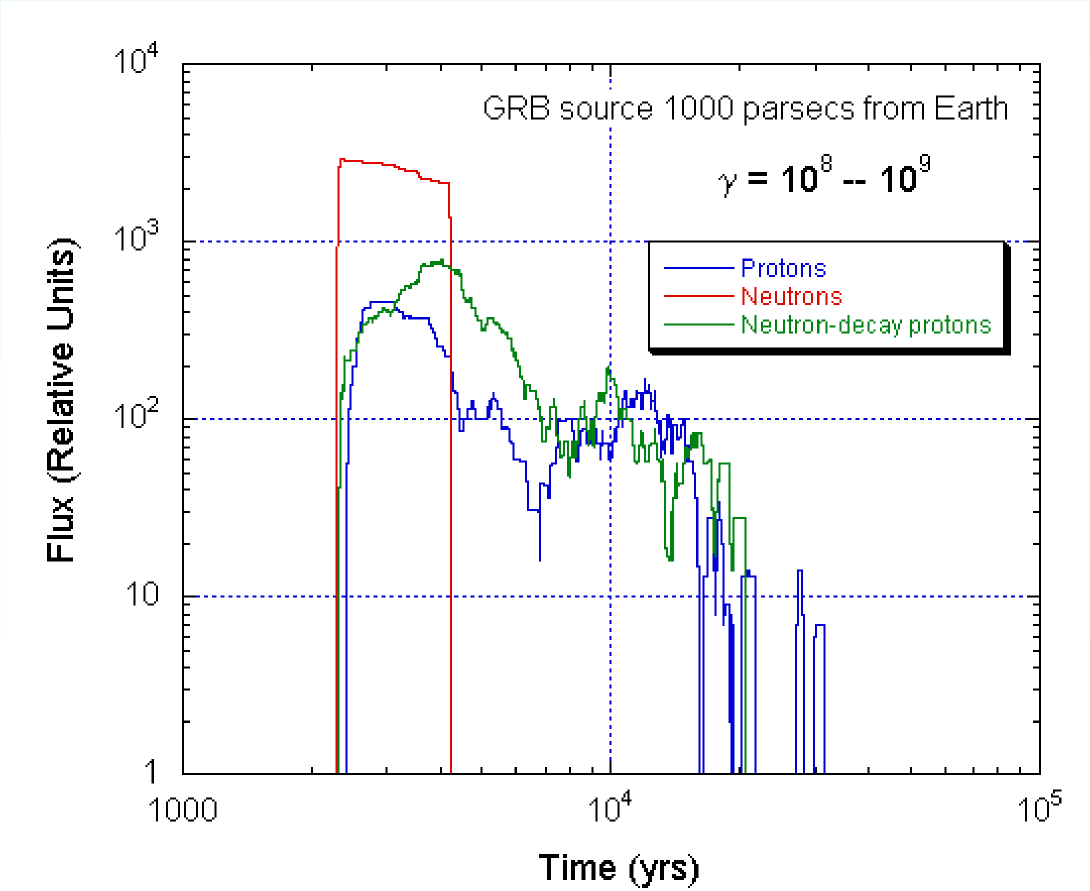
Melott et al. (2004) suggest that a GRB pointed towards Earth produced a lethal flux of high-energy photon and muon radiation flux that destroyed the ozone layer, killed plankton, and led to trilobite extinction in the Ordovician Epoch

However, geological evidence points toward two pulses; a prompt extinction and an extended ice age.

The prompt neutrons and gamma-rays from a GRB could have produced the prompt extinction. The delayed cosmic rays could have produced the later ice age

Flux of Cosmic Rays from GRB Jet Pointed towards the Earth

Fluxes of cosmic ray neutrons, neutron-decay protons, and protons passing near Earth as a function of time for cosmic ray Lorentz factors between 10^8 and 10^9. The source of high-energy cosmic rays is located 1000 parsecs from the Earth, with the GRB jet pointed in our direction.



As many as three phases of cosmic ray irradiation are found:

1. Prompt neutron (and gamma-ray) flux,
2. Neutron-decay protons,
3. Cosmic ray protons produced at the GRB source.

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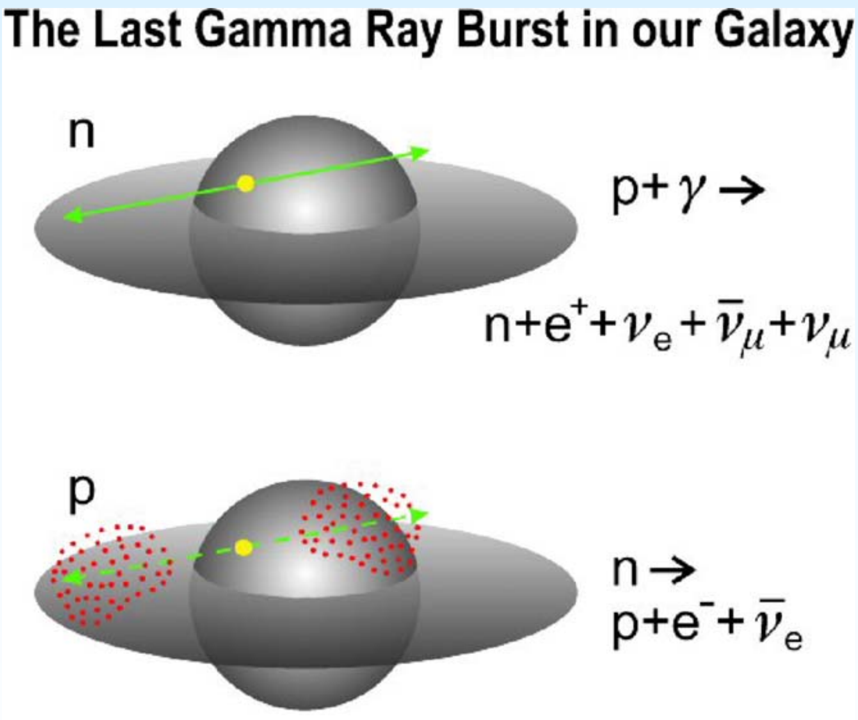
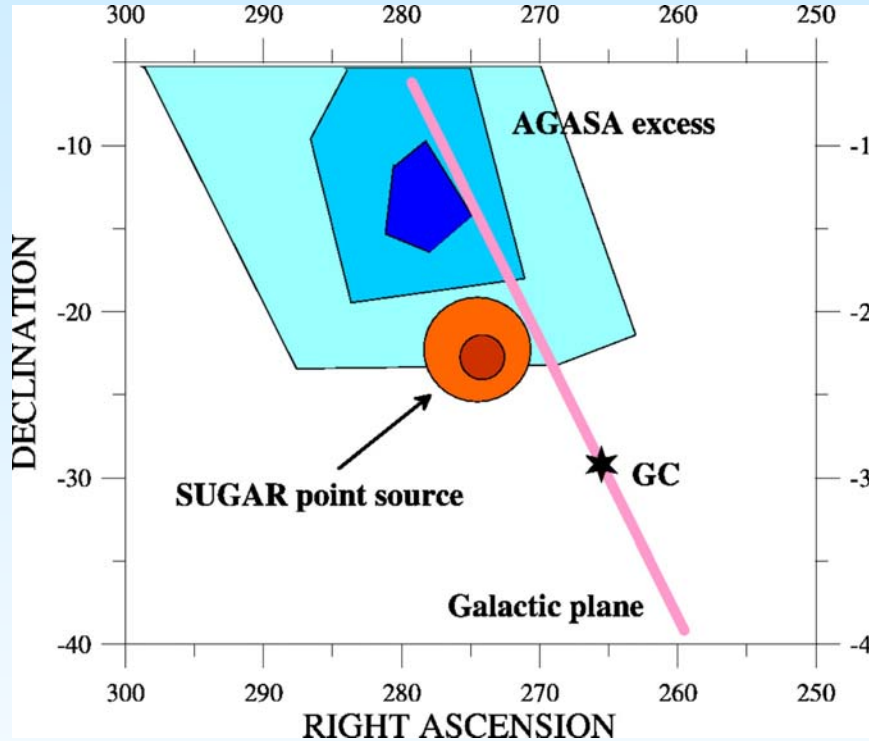
Evidence for high-energy (10^{18} eV) cosmic ray sources towards the Galactic Center



Medina-Tanco, Biermann et al. (2004)



Duration of a cosmic-ray neutron event from a GRB is short compared to the mean lifetime between GRBs; therefore model predicts no SUGAR excess

Summary

- Complete model where Cosmic Rays originate from
  1. SNe that collapse to neutron stars in the Galaxy ($E <\sim 10^{14}$ eV),
  2. SNe that collapse to black holes (GRBs) in the Galaxy (10^{14} eV $<\sim E <\sim 5\times10^{17}$ eV),
  3. Extragalactic SNe that collapse to black holes (GRBs) ($E >\sim 5\times10^{17}$ eV)

- GRB/Cosmic Ray model requires that GRBs are hadronically dominated

- High-energy neutrino detection from GRBs only if GRBs are hadronically dominated

- Anomalous hard γ-ray emission component in GRB 941017 due to hadronic cascade radiation inside GRB blast wave (during prompt phase) and synchrotron radiation of hyper-relativistic electrons formed by outflowing neutrons (during prompt and extended phase)

- Observation of GRB 941017 may provide first clear evidence for hadronic acceleration in GRBs and the sites where high-energy cosmic rays originate

- GRBs in the Milky Way could have produced earlier extinction events